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THE BOX INLET DROP SPILLWAY
AND ITS OUTLET

by Fred W. Blaisdell, M. ASCE,
and Charles A. Donnelly

HYDRAULICS DIVISION

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THIS PAPER

THE BOX INLET DROP SPILLWAY AND ITS OUTLET

Fred W. Blaisdell[1], M. ASCE, and Charles A. Donnelly[2]

SYNOPSIS

This paper reports model experiments made to determine the free flow capacity and the effect of submergence on flow over box inlet drop spillways and describes the development of an outlet for the spillway. For the use of the designer, data are presented for the determination of both the free flow capacity and the hydraulic proportions of the outlet structure. Design data to determine the effect of submergence on flow over the spillway are too voluminous to include in this paper.

Two control sections—the box inlet crest and the headwall opening—are shown to govern the head-discharge relationship. The control section changes from the former to the latter as the flow increases. Flow over the box inlet crest is affected by the head on the box inlet, the box inlet shape, the width of the approach channel, and the location of the dikes. These effects are described and the corrections which must be applied to the discharge coefficient are evaluated for a wide range of conditions. When the control section is at the headwall opening, the discharge coefficient varies with the depth of the box inlet. In addition, the head, which is measured from the crest of the box inlet, must be corrected by adding a distance which is a function of the relative depth of the box inlet. Discharge coefficients and head corrections are presented.

Submergence greatly affects the flow through box inlet drop spillways. The effect decreases as the flared outlet is widened and varies with the discharge, the greatest effect occurring at that discharge where the free flow control changes from the box inlet crest to the headwall opening.

The outlet structure can be adjusted to fit a wide variety of field conditions. It is possible to lengthen the straight section and to cover it to form a highway culvert. The stilling basin section sidewalls can flare if desired, thus permitting discharges into a narrow channel or onto a wide flood plain. Flaring the sidewalls also makes it possible to adjust the tailwater depth to the depth naturally available.

INTRODUCTION

The box inlet drop spillway may be described as a rectangular box open at the top and at the downstream end. An outlet structure is attached to the open end of the box inlet. A spillway and its outlet are shown in Fig. 1 and its general proportions and dimensions are defined in Fig. 2. Runoff water is directed to the crest of the box inlet by earth dikes and headwalls, enters over the

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upstream end and two sides, and leaves the spillway and enters the outlet through the open downstream end. The long crest of the box inlet permits large flows to pass over it with relatively low heads and correspondingly low dikes, yet the width of the spillway need be no greater than that of the downstream channel.
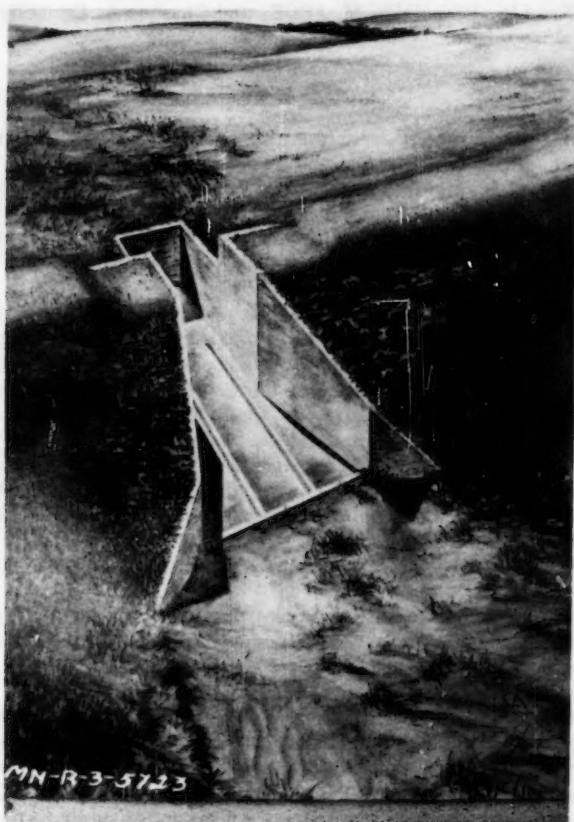
Fig. 1

There are uses for the box inlet drop spillway in the fields—among others—of irrigation, drainage, gully control, water conservation, and highways. As a gully control structure and as an outlet for artificial ponds in the field of soil and water conservation, it is used to control vertical drops of from 2 ft to 12 ft. As a drainage structure it is used to permit excess surface water to enter the drainage ditch without causing erosion of the ditch head or banks, and at the same time it provides an outlet structure for drain tile. In highway use the so-called straight section of the outlet can be lengthened and covered to form a culvert. The reader can perhaps anticipate other cases where the special characteristics of this type of spillway can be utilized to advantage.

PLAN

SECTION AT CENTER LINE

U S Department of Agriculture, Soil Conservation Service — Research
in Cooperation with the Minnesota Agricultural Experiment Station and
the St Anthony Falls Hydraulic Laboratory, University of Minnesota
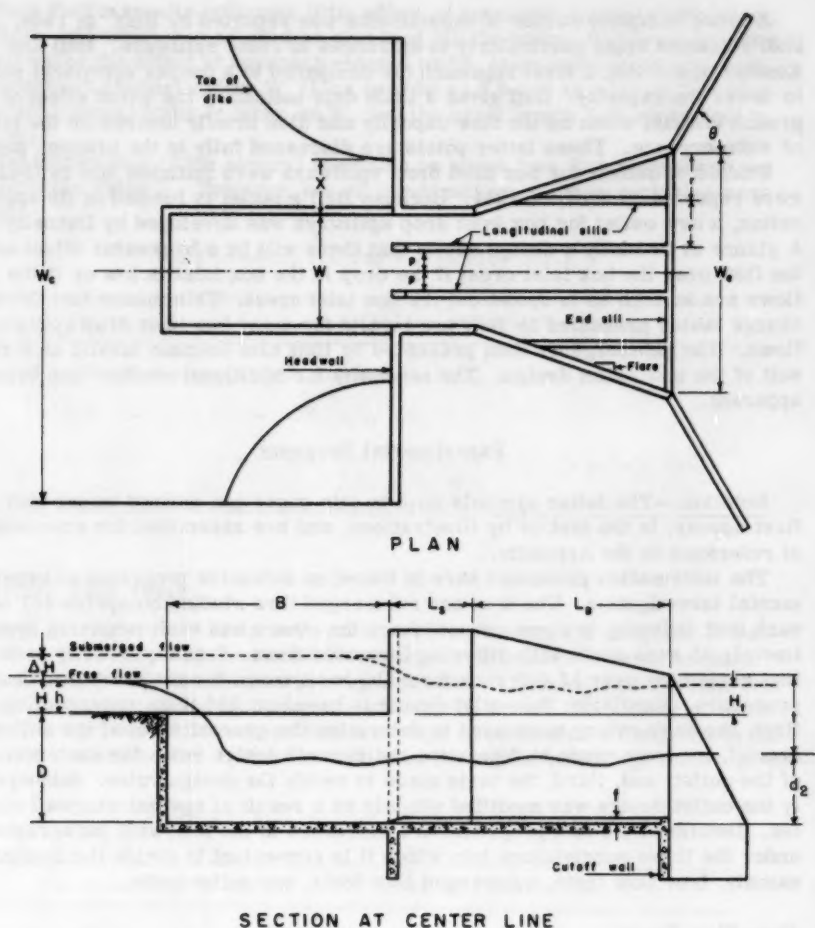
Fig. 2.--Proportions of the Box Inlet Drop Spillway

Previous Work

The earliest work on box inlet drop spillways to come to the attention of the authors is that reported by Kessler[3] in 1934. Some use of Kessler's design was made during the 1930's but it is now obsolete as far as the Soil Conservation Service program is concerned.

3. "Experimental Investigation of the Hydraulics of Drop Inlets and Spillways for Erosion Control Structures," by L. H. Kessler, 1934, Engineering Experiment Station Series No. 80, pp. 56-66, Bulletin of the University of Wisconsin.

534-3

A more complete series of experiments was reported by Huff[4] in 1944. Huff's results apply particularly to entrances to chute spillways. Huff and Kessler agree that a level approach (as compared to a deeper approach) serves to lower the capacity. Huff gives a little data indicating the great effect of approach channel width on the flow capacity and also briefly touches on the effect of submergence. These latter points are discussed fully in the present paper.

Studies of outlets for box inlet drop spillways were initiated late in 1942 and were reported by Huff[5] in 1944. Because Huff's outlet is limited in its application, a new outlet for box inlet drop spillways was developed by Donnelly.[6] A glance at Donnelly's design shows that there will be a backwater effect on the flow over the box inlet crest if the drop in the box inlet is low or if the flows are so high as to drown out the box inlet crest. This means that the discharge tables presented by Huff are invalid for many box inlet drop spillway flows. The submergence data presented by Huff also become invalid as a result of the new outlet design. The necessity for additional studies thus becomes apparent.

Experimental Program

Notation.—The letter symbols used in this paper are defined where they first appear, in the test or by illustrations, and are assembled for convenience of reference in the Appendix.

The information presented here is based on extensive programs of experimental investigation. The free and submerged flow studies comprise 361 tests, each test differing in some respect from the others and each requiring approximately 35 runs made with differing flow conditions. It can be readily seen that something over 12,000 runs form the background for the discharge design procedure. Similarly, the outlet design is based on 386 tests representing, first, the exploratory tests used to determine the general form of the outlet, second, the tests made to determine the general design rules for each element of the outlet, and, third, the tests made to verify the design rules. Subsequently the outlet design was modified slightly as a result of special wingwall studies. Details of the test programs are discussed in the following paragraphs under the three subdivisions into which it is convenient to divide the studies; namely, free flow tests, submerged flow tests, and outlet tests.

Free Flow Tests

An analysis of the dimensions of a number of box inlets constructed by the Soil Conservation Service indicated that relative box inlet depths D/W ranging from $\frac{1}{4}$ to 1 and relative box inlet lengths B/W ranging from 0.25 to 2 would cover the anticipated range of field conditions although the range of tests for B/W was from 0 to 4. Here W is the width, D is the depth, and B is the length, respectively, of the box inlet drop spillway.

4. "The Hydraulic Design of Rectangular Spillways," by A. N. Huff, February, 1944, SCS-TP-71, U. S. Dept. of Agriculture, Soil Conservation Service, Washington, D. C.
5. "Progress Report on Design of an Outlet Structure for Head Spillways," by A. N. Huff, December, 1944, U. S. Dept. of Agriculture, Soil Conservation Service, Washington, D. C. (Report is now out-of-print.)
6. "Design of an Outlet for Box Inlet Drop Spillway," by C. A. Donnelly, November, 1947, SCS-TP-63, U. S. Dept. of Agriculture, Soil Conservation Service, Washington, D. C.

Since Huff's results indicated little effect of approach channel width when $W_c/L \geq 3$, this width was adopted as standard for the tests. However, in order to determine the effect of approach channel width, tests were made with relative approach channel widths W_c/L as narrow as 0.4 and as wide as 10. The approach channel width is taken as W_c and the crest length L is equivalent to $2B + W$.

The magnitudes of the several variables on which free flow tests were run are listed in Table 1. However, not all combinations of these variables were tested.

TABLE 1.--Test Program - Free Flow Tests

Variable	Values of Variable Tested
B/W - - - - - - - -	0, 0.25, 0.5, 1, 2, 3, 4
D/W - - - - - - - -	1/8, 1/4, 1/2, 1
W_c/L - - - - - - - -	0.4, 0.6, 0.8, 1.0, 1.15, 1.3, 1.5, 2.0, 3.0, 5.0, 10.0

Submerged Flow Tests

About 50 exploratory tests were made before planning the program of submergence tests. Indications were that a very large number of tests would be required to define properly the submergence effect. Considerable thought was given to this phase of the test program in order to reduce the number of tests to a minimum yet to cover adequately the range of conditions anticipated in the field. The variables and their values utilized during the test program are given in Table 2.

TABLE 2.--Test Program - Submerged Flow Tests

Variable	Values of Variable Tested
B/W - - - - - - - -	0.5, 1, 2
D/W - - - - - - - -	1/4, 1/2, 1
W_e/W - - - - - - - -	1.0, 1.25, 1.5, 2.0
$Q/W^{5/2}$ - - - - - - - -	0.6, 1.0, 1.5, 2.0, 3.0, 4.0, 6.0

Outlet Tests

It was not possible to design in advance any clear-cut program for the outlet tests. Nevertheless, the program can be divided into three phases—the exploratory tests, the evaluation tests, and the check tests. The initial tests were exploratory and served to determine in a general way the important features of the outlet. During the next phase of the study, the proportions of the various features were varied one by one to discover how the performance of

the outlet was affected. The final phase of the study was begun after the design rules had been developed. These rules were checked by designing a series of outlets and testing them under the range of conditions that each was supposed to handle.

Apparatus and Procedure

Two different test setups were used for these tests. Both setups will be described briefly.

Free and Submerged Flow Tests

The experimental setup used for the box inlet drop spillway study was especially designed for making submergence tests. The special features incorporated into it also facilitated the rating tests. A general view of the test setup is shown in Fig. 3. Important features not shown in Fig. 3 are described in the following paragraph.
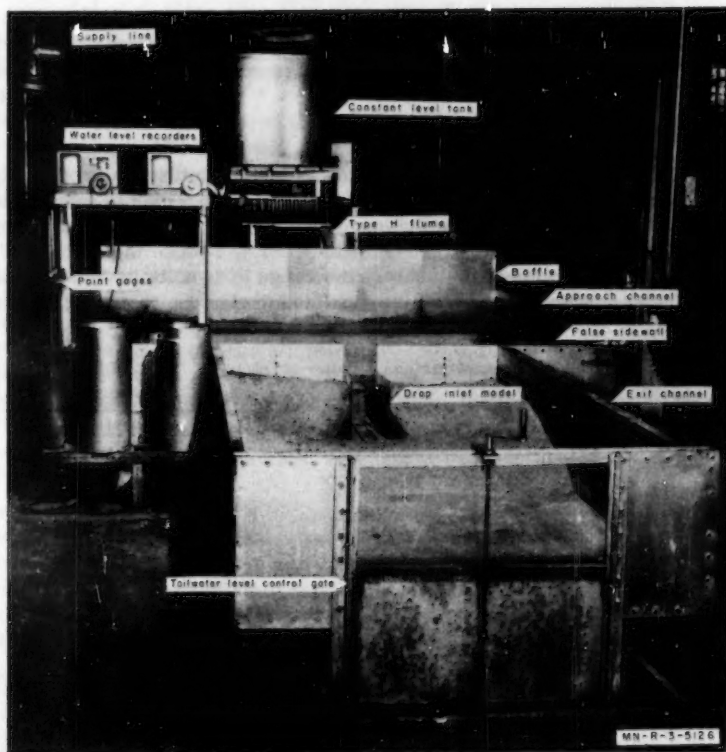

Fig. 3

The approach channel floor was of cement mortar and was level with the crest of the box inlet. The headwater piezometer opening was located at the center of the channel 3 ft 6 in. upstream from the headwall. The tailwater piezometer opening was located 5 ft 0 in. downstream from the headwall. Point gages were used in determining the water levels and water level recorders were used for control purposes. The recorders served to increase the reliability of the readings as well as to save time.

Outlet Tests

The arrangement of the test apparatus for the outlet tests is shown in Fig. 4. All models were halved (split along their longitudinal centerlines) and set against the glass panel in the channel as shown in Fig. 4. Previous experiments on culvert outlets have shown that identical results can be obtained from either full or half models.

Supply Line
Baffles
Point gage carriage
Glass observation panel
Sand bed
The model

Stop-logs

Baffles

Float

HS-flume

Supply line   Glass observation panel
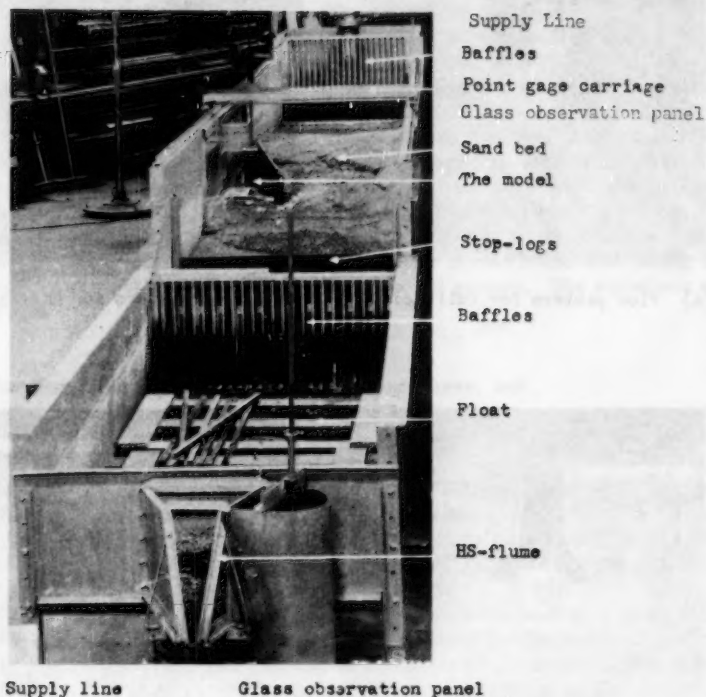
Fig. 4 Test Apparatus - Outlet Tests

Near the conclusion of the box inlet drop spillway outlet tests, this half-model method of conducting tests was checked on a full model half the size of the half models. A view of this model is shown in Fig. 5(c). After the full model had been tested, a lucite plate was placed at the centerline of the structure to give, in effect, two half models as shown in Fig. 5(d) and the test was repeated. The results of the tests are shown in Fig. 5. Confetti has been sprinkled on the water surface of the flow photographs, Figs. 5(a) and 5(b), to show the stream lines. A careful comparison of the two photographs will show

that the flow patterns are identical within the limits of precision of the experiment. The scour patterns are compared in Figs. 5(c) and 5(d). A small disagreement in scour patterns will be noted between the two halves of Fig. 5(d). However, the bed slopes are small and a considerable displacement in plan position of the contours represents only small differences between the depths on either side of the centerline.

Ordinary concrete sand passing an 8-mesh screen was used for the stream bed downstream from the outlet. The erosion of the sand bed below the level of the outlet floor was used as a measure of the efficiency of the outlet.
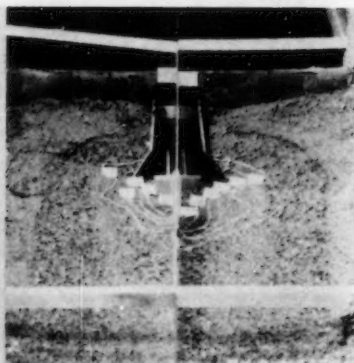

(a) Flow pattern for full model.   (b) Flow pattern for half model.
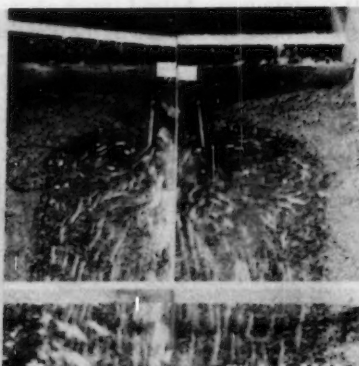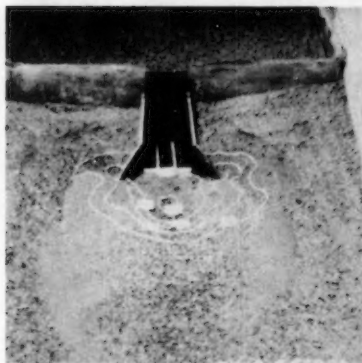
(c) Scour pattern for full model.   (d) Scour pattern for half model.

Fig 5.--Comparison of Results Obtained
Using Full and Half Models.

Considerable study was necessary to find the best method for analyzing the data. The adopted method will be described and will be followed by separate presentations of the results obtained when the control is at the box inlet crest and when the control is at the headwall opening.

Analysis of Data

Both the flow over the box inlet crest and through the headwall opening are theoretically proportional to the three-halves power of the head or

$$Q \propto H^{3/2} \tag{1}$$

Use was made of this fact to plot all the data for each test on a single sheet. However, to simplify the analysis, both sides of Eq. 1 were raised, before plotting, to the two-thirds power. The advantage of this type of plot is that the point where the flow control section shifts from the box inlet crest to the headwall opening can be readily determined. Also, if the data points fall on a straight line it is an indication that the theoretical exponent is correct.

A typical plot of data is shown in Fig. 6. It will be noticed that a number of points fall on neither the box inlet crest nor the headwall opening curves in the vicinity of their intersection. These points were not used in computing the rating curves. In addition, a few of the lowest points were discarded when they fell off the curve, probably as a result of surface tension effects.

The constants in the equations for the discharge given in Table 3 were determined by the method of least squares after it was found that fitting the curves by eye resulted in intolerable personal errors. The equations used had the form

$$Q = c_1 L \sqrt{2g} \; (H - H_{01})^{3/2} \tag{2}$$

for the box inlet crest portion of the rating curve, and

$$Q = c_2 W \sqrt{2g} \; (H - H_{02})^{3/2} \tag{3}$$

for the headwall opening portion of the rating curve.

Referring to Fig. 6, it will be noticed that the data points fall on straight lines except for those near the intersection of the two curves and for one or two of the lowest flows. This observation, with minor exceptions, is characteristic of all the data obtained during the tests. The deduction from this observation is that the theoretical exponent is correct.

It will be noticed that neither of the curves shown in Fig. 6 pass through the origin of coordinates. This had been anticipated for the headwall opening portion of the rating curve because the assumption of the origin of heads at the crest of the box inlet is obviously incorrect and the form of Eq. 3 was adopted, for one reason, so the correction H_{02} could be obtained. However, there was no reason to believe that H_{01} in Eq. 2 would be other than zero. The fact remains that H_{01} was consistently found to be greater than zero to a degree that left no doubt as to its statistical significance.

At first it was thought that the determination of the zero reading of the head gage was in error, but repeated checks eliminated this possibility. The possibility of surface tension effects is also eliminated by the manner in which the curve is drawn. The only conclusion that can be reached at this time is that the meaning of H_{01} has so far eluded detection.

Table 3
SUMMARY OF DATA—FREE FLOW TESTS

Test Number	B/w	B/D	D/w	w_c/L	w_o/w	Equation 2			Equation 3			
						c_1	R_{01}	N_L	c_2	R_{02}	$\dfrac{R_{02}}{D}$	N_V
49	2.0	2.0	1.0	3.0	2.0	0.416	0.006	9	0.414	-0.370	-0.740	8
77				2.0		0.399	0.007	27	0.449	-0.335	-0.670	10
78				1.5		0.390	0.008	27	0.739	-0.340	-0.680	11
79				1.3		0.378	0.008	29	0.461	-0.318	-0.636	10
80				1.15		0.366	0.008	16	0.445	-0.332	-0.664	12
81	1.0	1.0	1.0	1.0		0.346	0.010	22	0.414	-0.364	-0.728	9
82a				0.8		0.307	0.007	20	0.560	-0.236	-0.472	5
83				0.6		0.234	0.005	13	- - - No data obtainable - - -			
83a				0.6		0.235	0.007	9				
84				0.4		0.157	0.006	24				
85		1.0	1.0	3.0		0.402	0.004	14	0.432	-0.253	-0.506	9
114				2.0		0.416	0.004	16	0.423	-0.263	-0.526	10
115 & 115a				1.5		0.407	0.005	13	0.433	-0.252	-0.504	21
116				1.3		0.400	0.006	11	0.446	-0.239	-0.478	7
117				1.0		0.364	0.006	13	0.468	-0.213	-0.426	8
118				0.8		0.304	0.005	16	- - - Insufficient data - - -			
119				0.6		0.228	0.007	23	- - - No data obtainable - - -			
120				0.4		0.153	0.006	13	0.434	-0.249	-0.498	8
121				1.15		0.385	0.006	12	0.410	-0.280	-0.560	6
122				5.0		0.431	0.005	11	0.402	-0.152	-0.304	6
123	0.5	0.5	1.0	10.0		0.436	0.005	9	- - - No data obtainable - - -			
124				0.6		0.234	0.008	23				
125				0.8		0.302	0.004	25	0.457	-0.119	-0.238	11
126				1.0		0.364	0.006	10	0.430	-0.142	-0.284	11
127				1.15		0.396	0.006	8				
128				1.3		0.410	0.006	6	0.377	-0.197	-0.394	7
129				1.5		0.421	0.006	11	0.384	-0.183	-0.366	13
130				2.0		0.439	0.007	7	0.393	-0.169	-0.338	11
131				5.0		0.433	0.004	6	0.394	-0.160	-0.322	11
132				3.0		0.445	0.006	13	0.398	-0.158	-0.316	12

ID													
165			0.25	3.0		0.405	0.000	7	0.424	-0.059	-0.118	15
166	0.25	1.0	0.0	2.0		0.297	-0.003	8	0.434	-0.060	-0.120	17
167	0.0	1.0	0.0	3.0		0.423	0.002	24	0.423	0.002	0.004	25
168	2.0	0.5	4.0	2.0		0.446	0.007	25	0.446	0.007	0.014	25
169 & 169a				3.0		0.392	0.004	18	0.351	-0.227	-0.908	17
226	1.0		2.0			0.439	0.004	17	0.356	-0.199	-0.796	19
227	0.5		1.0			0.447	0.005	15	0.351	-0.136	-0.544	28
252	0.25		0.5			0.429	0.001	11	0.361	-0.079	-0.316	33
253	0.0	0.25	0.0			0.420	0.002	36	0.420a	0.002a	0.008a	34b
254	2.0		8.0			0.411	0.005	11	0.366b	-0.016b	-0.056b	37
285	1.0		4.0	3.6		0.388	0.002	10	0.334	-0.116	-0.928	
324	0.5		2.0	0.6		0.467	0.007	12	0.340	-0.113	-0.904	30
330	0.25		1.0	1.5		0.476	0.005	6	0.352	-0.085	-0.680	26
331	0.0		0.0	3.0		0.456	0.006c	13	0.324	-0.060	-0.460	22
332		0.125				0.417c	0.003c	4	0.368	-0.014	-0.112	27
						0.406	0.007	7	0.349	-0.007	-0.112	31
333			2.0	0.6		0.499	0.010	10	0.341	-0.032	-0.512	29
334			0.0	1.0		0.208	0.011	56	0.415	0.011	0.176	46
335	0.25		8.0	1.5		0.337	0.011	10	0.356	-0.036	-0.576	28
336	0.5			3.0		0.334	0.012	7	0.346	-0.035	-0.608	30
337				0.4		0.347	0.012	6	0.341	-0.099	-0.624	32
338	1.0			0.6		0.235	0.013	12	0.349	-0.042	-0.672	25
339			8.0	1.0		0.239	0.011	10	0.340	-0.046	-0.736	28
340				1.5		0.252	0.012	8	0.345	-0.042	-0.672	31
341				3.0		0.235	0.010	12	0.343	-0.042	-0.672	33
342				0.4		0.167	0.011	10	0.343	-0.042		
343				0.4		0.158	0.014	7	0.346	-0.045	-0.720	29
344	2.0		16.0	0.6		0.143	0.011	11	0.346	-0.044	-0.704	33
345				1.0		0.139	0.009	11	0.343	-0.044	-0.704	29
346				1.5		0.140	0.011	10	0.343	-0.043	-0.688	38
347				3.0		0.142	0.011	9	0.338	-0.047	-0.752	30
348	4.0	1.0	4.0	2.0		0.389	0.002	24	0.361	-0.499	-0.918	23
349	3.0	1.0	3.0	2.0		0.396	0.004	18	0.399	-0.463	-0.806	21

(No data obtainable)
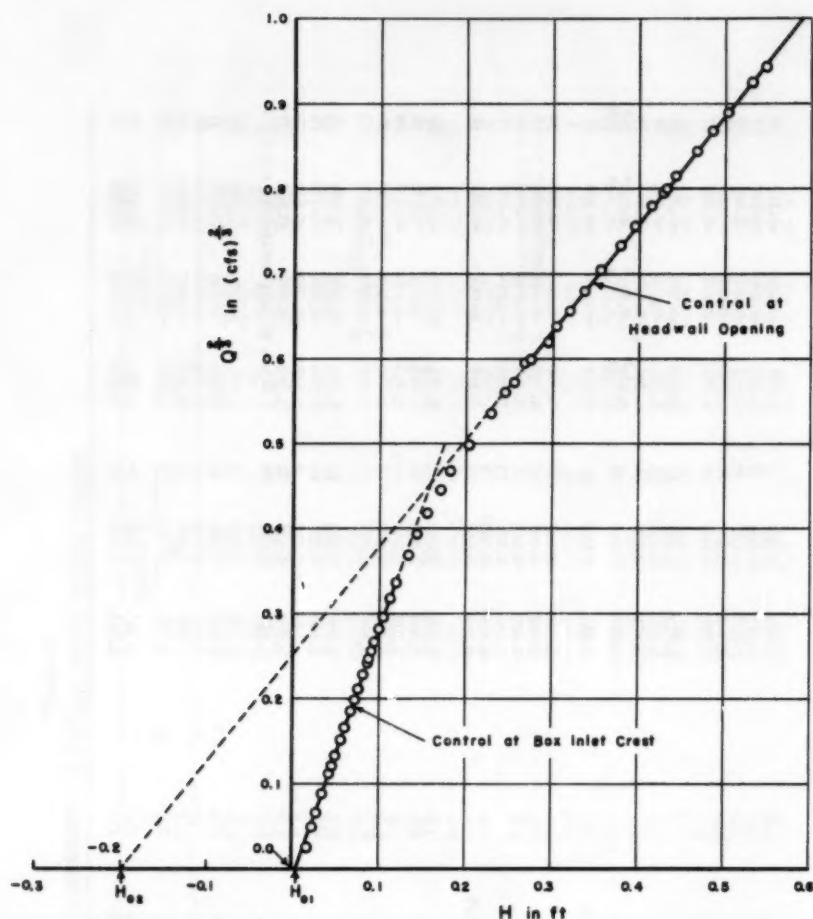
aTree name   bNo air under navoe   cNo end sill

Fig. 6.—Typical Plot of Data

Control at Crest of Box Inlet

Four factors which affect the flow through box inlet drop spillways when the control section is at the crest of the box inlet are discussed in the following subsections. In the concluding subsection the precision of the results is discussed.

Although it was shown by Kessler and Huff that the level of the approach channel will affect the discharge, no tests were made to evaluate this effect; the approach channel surface was level with the box inlet crest to simulate a natural approach channel silted level full.

Effect of Position of Dike.—Free access to part of the box inlet crest is cut off as the dike is moved closer to the crest of the box inlet. Although very little data were obtained, information which can be utilized to evaluate the dike effect will be presented for its qualitative value.

At the point where the toe of the dike just touches the crest, $X = 0$. Tests were made with $X/H = 0$, 0.7, 1.4, 2.9, 5.7, and ∞ (no dike) where H is the head for which the spillway is designed. The relative head H/W at which tests were made was 0.35. Since the dike slope was 1 on 3, the toe of the dike projected upstream 3H from the headwall. The tests were conducted for only a single box inlet having a relative length $B/W = 2$. The ratio of the discharge in a spillway with a dike to the discharge in the same spillway without a dike was computed for each of the dike positions with the results shown in Table 4 for $B/W = 2$. Apparently the toe of the dike should be located from 3H to 5H from the box inlet crest in order to minimize the dike effect.

If the effect of the dike on the discharge over other box inlets can be assumed to be inversely proportional to the length of the crest, then for a box inlet shape of $B/W = 1$, where the crest length is 3W as compared to 5W when $B/W = 2$, the decrease in the relative discharge obtained above will be $5W/3W$ or 1.7 times as great. The corresponding figure for $B/W = 0.5$ is $5W/2W$ or 2.5. Based on these assumptions, Table 4 has been prepared to facilitate the making of corrections for the dike effect. The importance of keeping the toe of the dike well away from the box inlet crest is quite apparent from the values shown therein.

In using the values shown in Table 4 to determine the dike effect, it should be kept in mind that the data are too few to permit the determination of any completely reliable figures. The data are presented here in the absence of any better information primarily for their qualitative value.

TABLE 4.—Correction for Dike Effect — Control at Box Inlet Crest

$\dfrac{B}{W}$	X/H					
	0.0	0.7	1.4	2.9	5.7	∞
2.0 (actual)	0.84	0.85	0.93	0.97	0.99	1.00
1.0 (estimated)	0.73	0.75	0.88	0.95	0.98	1.00
0.5 (estimated)	0.60	0.62	0.82	0.92	0.98	1.00

Effect of Approach Channel Width.—One phase of the present test program was designed to determine the effect of the width of the approach channel quantitatively and accurately. The results are presented in Fig. 7 in dimensionless form. The discharge coefficient c_1 was divided by the average discharge coefficient for channel widths equal to or greater than three crest lengths $c_{1, W_c/L \ge 3}$ before plotting. This was so the plotted values would directly indicate the throttling effect of the narrower approach channel. The tests with the deeper box inlets (larger D/W) are the most reliable since they cover a larger range of discharges than did those for the shallower box inlets; the data obtained on the deeper box inlets were given the greatest weight in drawing the curves.

The relative discharge coefficient is unaffected by approach channel widths equal to or greater than three times the length of the box inlet crest. Therefore, all design criteria are based on wide approach channels and the curve of Fig. 7 is suggested for use in correcting for the effect of narrow channels.
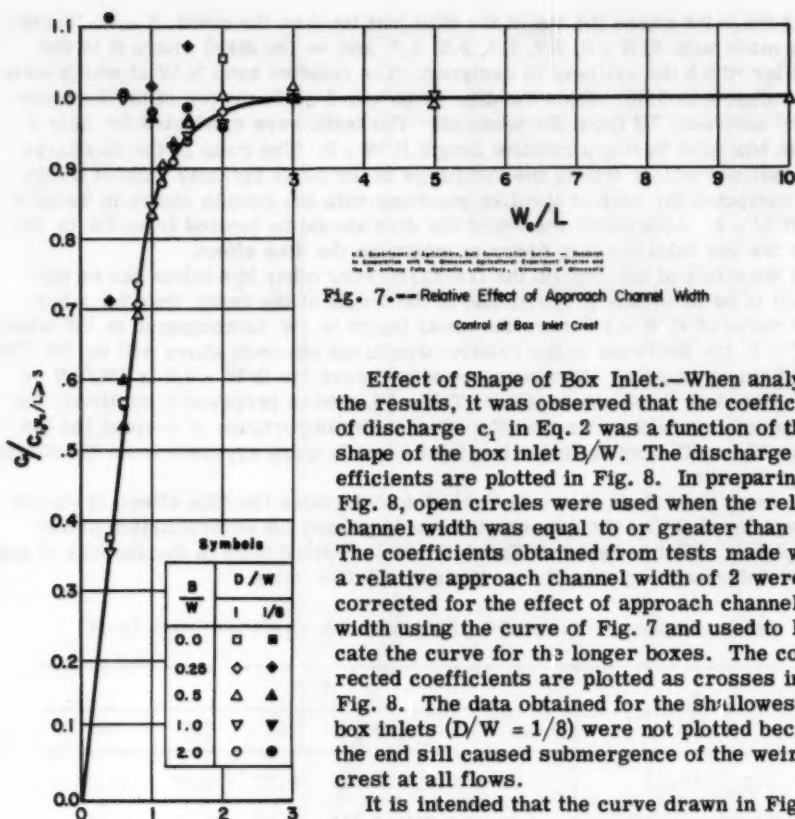
Fig. 7.—Relative Effect of Approach Channel Width
Control at Box Inlet Crest

U.S. Department of Agriculture, Soil Conservation Service — Research
in Cooperation with the Minnesota Agricultural Experiment Station and
the St. Anthony Falls Hydraulic Laboratory, University of Minnesota

Symbols

$\frac{B}{W}$	D/W	
	1	1/8
0.0	□	■
0.25	◇	◆
0.5	△	▲
1.0	▽	▼
2.0	○	●

Effect of Shape of Box Inlet.—When analyzing the results, it was observed that the coefficient of discharge c_1 in Eq. 2 was a function of the shape of the box inlet B/W. The discharge coefficients are plotted in Fig. 8. In preparing Fig. 8, open circles were used when the relative channel width was equal to or greater than 3. The coefficients obtained from tests made with a relative approach channel width of 2 were corrected for the effect of approach channel width using the curve of Fig. 7 and used to locate the curve for the longer boxes. The corrected coefficients are plotted as crosses in Fig. 8. The data obtained for the shallowest box inlets ($D/W = 1/8$) were not plotted because the end sill caused submergence of the weir crest at all flows.

It is intended that the curve drawn in Fig. 8 be used for design purposes. In spite of the scatter in the data, particularly for the short box inlets (low B W), it is felt that values taken from the curve are valid to within ± 10%.

A correction scale has been added at the right side of Fig. 8. This scale is based on the assumption that no correction is required to the discharge coefficient of 0.4275 when $B/W = 1$, but that a correction is required for other box inlet shapes.

Variation of Discharge Coefficient with Head.—Although the coefficient c_1 in Eq. 2 is a constant, the use of Eq. 2 with its zero-flow head correction, which insures the constancy of c_1, is open to some objection. Accordingly, a means was sought to eliminate the zero-flow head correction altogether even though this necessitated the use of a variable discharge coefficient. The resulting equation for discharge over the box inlet crest has the form

$$Q = c_3 \, L \sqrt{2g} \, H^{3/2} \tag{4}$$

where c_3 now varies with the head.

To determine the coefficient of discharge in Eq. 4, c_3 was computed for each run of all pertinent tests. The coefficient c_3 was then corrected for the effect of approach channel width and box inlet shape. The corrected discharge
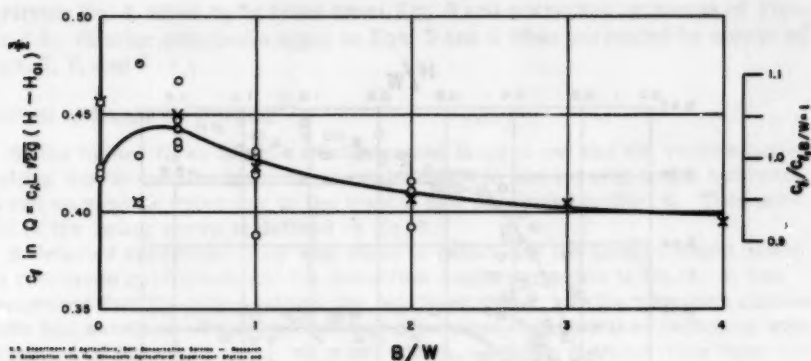
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Fig. 8.—Effect of Box Inlet Shape on Discharge Coefficient

Control at Box Inlet Crest

$$\frac{W_c}{L} \geqslant 3$$

coefficients are plotted in Fig. 9 against relative head H/W. The only data not appearing in Fig. 9 are those obtained for shallow boxes where submergence caused by the sill at the outlet exit affects the discharge even at very low flows. Some shallow box data has been included for runs where the end sill was removed. Data from 51 of the 62 tests listed in Table 3 appear in Fig. 9.

A mean curve has been drawn as a solid line in Fig. 9. The coefficient of discharge for a given relative head may be taken from this curve, multiplied by the approach channel width correction and the box inlet shape correction, and substituted in Eq. 4 to determine the capacity of the box inlet drop spillway when the box inlet crest controls the discharge. A second method for determining the discharge is outlined in the following paragraph using the correction scale at the right of Fig. 9.

It will be noticed that the discharge coefficient is constant in Fig. 9 when H/W is greater than 0.6. Therefore, Eq. 4 can be written
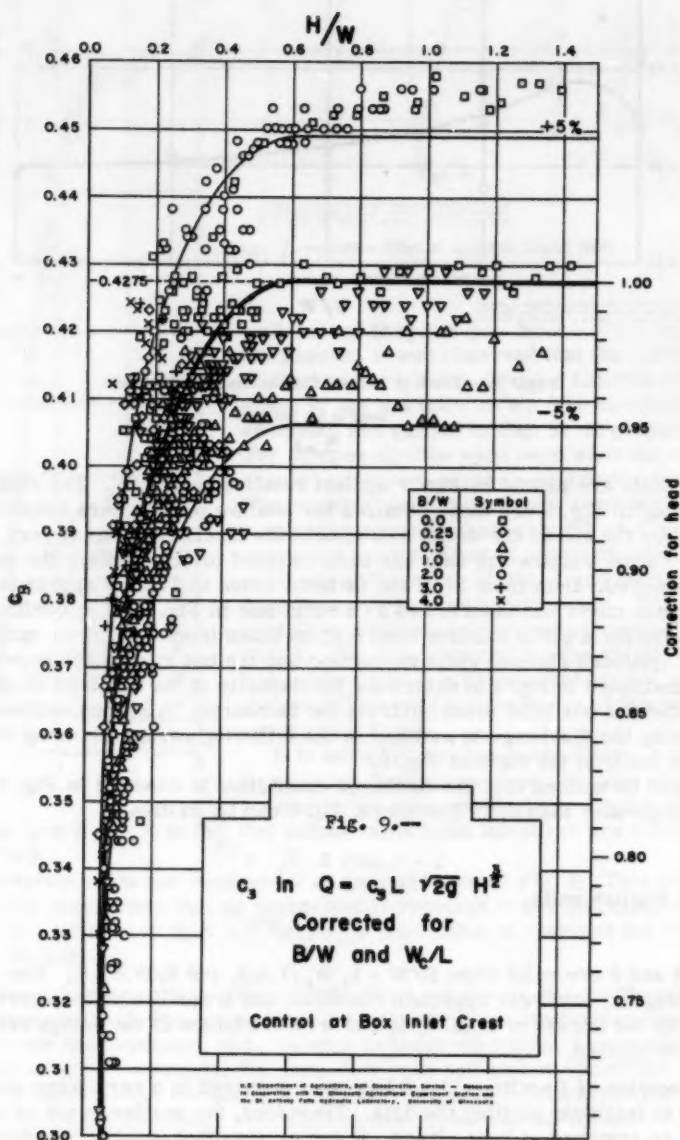
$$Q = 0.4275 \; L \sqrt{2g} \; H^{3/2} \tag{5}$$

or, in English units,

$$Q = 3.43 \; L \; H^{3/2} \tag{6}$$

Eqs. 5 and 6 are valid when $B/W = 1$, $W_c/L \geq 3$, and $H/W \geq 0.6$. For other box inlet lengths, narrower approach channels, and lower heads, the corrections given by the curves of Figs. 7, 8, and 9 or the tables of the design reports[7] must be applied.

Precision of Results.—Fig. 9 has been prepared to a very large scale in order to facilitate plotting the data. Therefore, the scatter is not as great as might be assumed at first glance. It can be seen that most of the observed data fall within + 5% of the mean line. Therefore, Fig. 9 may be considered as

7. "Hydraulic Design of the Box Inlet Drop Spillway," by F. W. Blaisdell and C. A. Donnelly, January 1951, Technical Paper No. 8, Series B, of the St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, now reprinted as SCS-TP-106, U. S. Dept. of Agriculture, Soil Conservation Service, Washington, D. C.

Fig. 9.—

c_3 in $Q = c_3 L \sqrt{2g} H^{\frac{3}{2}}$
Corrected for
B/W and W_c/L

Control at Box Inlet Crest

U.S. Department of Agriculture, Soil Conservation Service — Research in cooperation with the Minnesota Agricultural Experiment Station and the St. Anthony Falls Hydraulic Laboratory, University of Minnesota

verifying Eq. 4 when c_3 is taken from Fig. 9 and corrected by means of Figs. 7 and 8. Similar comments apply to Eqs. 5 and 6 when corrected by means of Figs. 7, 8, and 9.

Control at Headwall Opening

At the higher flows the box inlet becomes flooded out and the section controlling the flow shifts from the box inlet crest to the opening in the headwall, as can be seen by referring to the typical plot presented in Fig. 6. This portion of the rating curve is defined by Eq. 3.

A detailed analytical study was made to determine the factors which affect the discharge coefficient and the zero-flow head correction in Eq. 3. It was discovered that the dike position, the box inlet shape, and the approach channel width had no effect on the discharge coefficient c_2 but that the coefficient was a function of the depth of the box inlet. With regard to the zero-flow head correction H_{02}, it was discovered that H_{02} was independent of the approach channel width and the dike position but was a function of both the relative length B/W and the relative depth D/W of the box inlet. Separate subsections of the report are devoted to the effect of the relative depth of the box inlet on the discharge coefficient and to the head correction.

Effect of Depth of Box Inlet on Discharge Coefficient.—When the discharge coefficient c_2 in Eq. 3 is plotted against the relative depth of the box inlet D/W it is found that c_2 increases with D/W. This is shown in Fig. 10. While there is considerable spread to the data, other plots not presented here show that c_2 is independent of both B/W and W_c/L and it seems unlikely that the spread can be decreased.

For design purposes the solid curve drawn in Fig. 10 is suggested for use in determining the coefficient of discharge in Eq. 3.
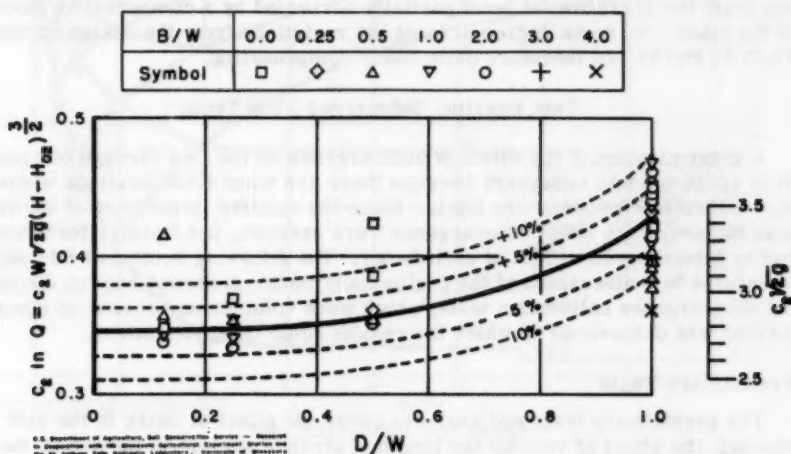
B/W	0.0	0.25	0.5	1.0	2.0	3.0	4.0
Symbol	□	◇	△	▽	o	+	×

Fig. 10.—Coefficient of Discharge

Control at Headwall Opening

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Head Correction.—The tests showed that the head correction is independent of both the approach channel width and the width of the box inlet, but that it is a function of the ratio of the box inlet length to its depth B/D. In Fig. 11 the ratio H_{02}/D has been plotted against B/D. There it will be noticed that the data for box inlets having relative depths D/W of 1, 1/2, and 1/4 fall on a single curve, but that for a relative box inlet depth of 1/8 the data fall on a separate well-defined curve. The reason for this has not been discovered.

In view of the fact that shallow boxes will be uneconomical in most cases for the higher flows where the headwall opening controls the discharge, the solid curve of Fig. 11 is presented for design purposes for box inlets equal to or greater in depth than W/4. In order to cover the relative box inlet depths between 1/4 and 1/8 as well as the deeper box inlets, the data has been plotted in a different form in Fig. 12. Although Fig. 11 is simpler to use than Fig. 12, Fig. 12 may be used in place of Fig. 11 and must be used for the shallower boxes.

Precision of Results.—Dashed curves have been added to Fig. 10 parallel to the solid curve and 5% and 10% above and below it to indicate the spread of the data. Although occasional data points fall outside the 10% limits, sufficient data fall inside this range to indicate that the coefficient of discharge reasonably can be expected to be within 10% of the value given by the solid curve.

With regard to the head correction, it appears that the curve of Fig. 11 can be expected to give this correction to within about 10%, in general. At the low values of B/D the curve is steep and it seems likely that there the head correction may vary by as much as 20% from the curve. Little can be said regarding the accuracies obtainable through the use of Fig. 12 but it seems likely that the comments made regarding Fig. 11 also apply to Fig. 12.

It was noted when analyzing the data that the coefficient of discharge and the head correction vary in such a manner as to indicate that a deviation of one from the curve was at least partially corrected by a compensating deviation of the other. To some degree at least the variations from the design curves of Figs. 10 and 11 are therefore quite likely compensating.

Test Results: Submerged Flow Tests

A determination of the effect of submergence on the flow through box inlet drop spillways was necessary because there are many field locations where high tailwater elevations are likely. Since the relative importance of the various factors which affect submergence were unknown, preliminary tests were run to determine the effect of each factor. The following section of this paper is devoted to a discussion of the preliminary tests. A second section discusses the submergence calibration tests, which were voluminous because no simple method was discovered by which the results could be systematized.

Preliminary Tests

The preliminary tests and analyses cover the effect of banks in the exit channel, the effect of varying the length of straight section in the outlet, the effect of the width of the outlet, and the effect of varying the rate of flow. A separate subsection is devoted to each of these effects.

Effect of Banks in Exit Channel.—Since it would be more convenient if it were not necessary to simulate the exit channel, a test was made to determine whether the submergence curve was affected by the presence or absence of the downstream channel.
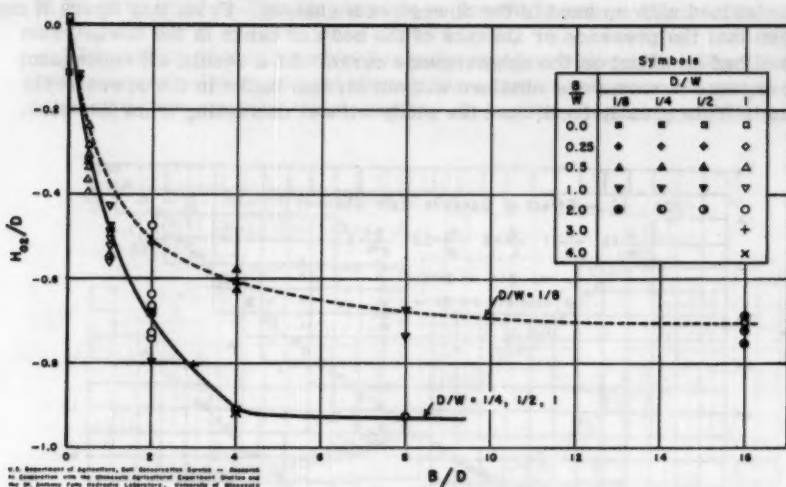
Fig. 11.—Relative Head Correction for D/W ≥ 1/4
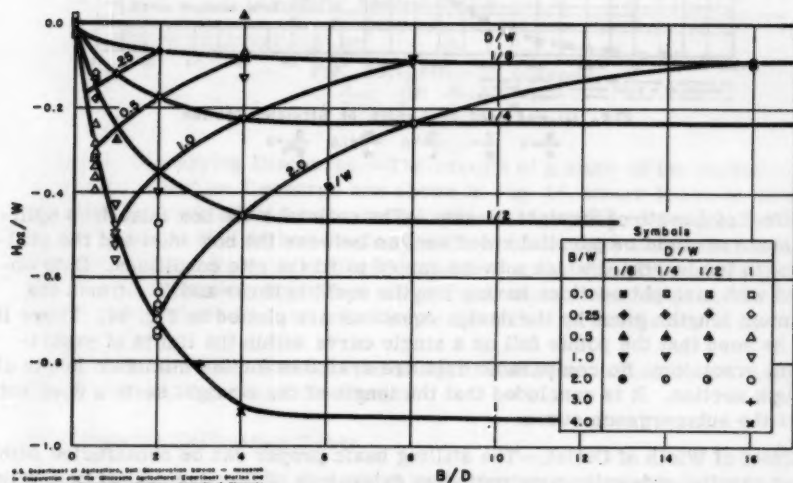
Control at Headwall Opening

Fig. 12.—Relative Head Correction

Control at Headwall Opening

In Fig. 13, the data points shown as triangles were obtained with a down-stream channel filled with sand, the shape being formed by water running over it with the tailwater at about its normal level. The data points shown as circles were obtained with no sand in the downstream channel. From this figure it can be seen that the presence or absence of the bed and banks in the downstream channel had no effect on the submergence curve. As a result, all subsequent submergence curves were obtained without stream banks in the downstream channel. This greatly facilitated the study without detracting from its value.
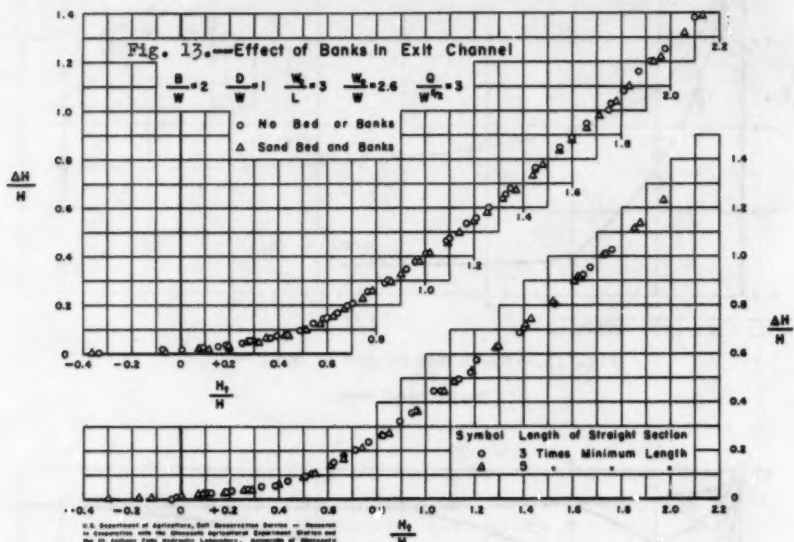

Fig. 13.—Effect of Banks in Exit Channel

$$\frac{B}{W}=2 \quad \frac{D}{W}=1 \quad \frac{W_1}{W}=3 \quad \frac{W_2}{W}=2.6 \quad \frac{Q}{W^{\frac{5}{2}}}=3$$

o No Bed or Banks
△ Sand Bed and Banks

Symbol	Length of Straight Section
o	3 Times Minimum Length
△	5 " " "

Fig. 14.—Effect of Length of Straight Section

$$\frac{B}{W}=2 \quad \frac{D}{W}=1 \quad \frac{W_1}{L}=3 \quad \frac{W_2}{W}=1.8 \quad \frac{Q}{W^{\frac{5}{2}}}=3$$

Effect of Length of Straight Section.—The outlet for the box inlet drop spill-way has a straight or parallel sided section between the box inlet and the still-ing basin the length of which may be varied to fit the site conditions. Data ob-tained with straight sections having lengths equal to three and five times the minimum lengths given by the design equations are plotted in Fig. 14. There it may be seen that the points fall on a single curve within the limits of experi-mental precision. No comparable data are available for the minimum length of straight section. It is concluded that the length of the straight section does not affect the submergence curve.

Effect of Width of Outlet.—The stilling basin proper can be constructed with either parallel sidewalls constructed as extensions of the straight section walls or with flaring sidewalls. If flaring sidewalls are used, it is likely that there will be a recovery of velocity head in the outlet that may mitigate the submer-gence effect. Therefore, the influence of flaring outlet sidewalls was investi-gated.

A study of the data indicates that the rate of flare of the outlet sidewalls, within reasonable limits, does not affect the submergence curves. Flares tested varied from 1 in ∞ (no flare) to 1 in 2, the maximum permitted by the outlet design.

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It is the width of the outlet at its downstream end W_e that determines the amount of energy recovered in the outlet. This is shown in Fig. 15. As would be anticipated, the effect of the width decreases as the width increases until, in the case cited in Fig. 15, there is no benefit in using outlets wider than about 1.5W.

The results of this investigation show the great effect of width of outlet and indicate the necessity of considering the outlet width as one of the variables in a study of submergence effects on flow through box inlet drop spillways.

Fig. 15.—Effect of Width of Outlet
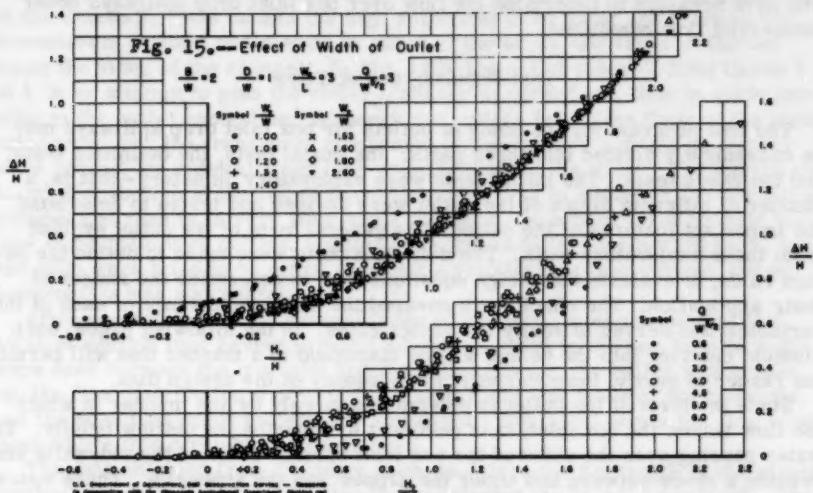
Fig. 16.—Effect of Discharge

Effect of Varying Discharge.—The results of a study of the variation in submergence effect on discharge are shown in Fig. 16, where it can be seen that the submergence effect increases with the discharge up to the point where $Q/W^{5/2} = 4$. At still higher discharges the submergence effect decreases. An excellent correlation was obtained showing that the discharge which produces the greatest submergence effect corresponds to that discharge on the free flow rating curve where the control changes from the box inlet crest to the headwall opening.

As a result of this phase of the study, it can be seen that the submergence effect is a function of the discharge.

Submergence Calibration Tests

The preliminary tests discussed in the foregoing paragraphs bear out the comments made by King when commenting on the submerged weir experiments made by Bazin. King[8] says, "Each type of weir is a problem in itself and if the laws governing [submerged] flow over it are to be determined, each requires an extensive experimental investigation, covering a wide range of conditions."

8. "Handbook of Hydraulics," by Horace Wm. King, (2nd Edition), 1929, p. 162, McGraw-Hill Book Company, Incorporated, New York.

The test program was designed to provide the "extensive experimental investigation" which King says is required. The range of variables covered is given in Table 2. The data for each of the 36 models or variations were plotted on separate sheets, each of the six constant discharges recorded on each sheet being represented by a different curve. Fig. 16 is representative of these plots. The space required to present them does not permit the inclusion of the submergence curves in this paper. However, the 216 submergence curves (less the data points) have been prepared for design use, and are presented in a section of the design report[9] which has been prepared especially for use by those who have occasion to determine the flow over box inlet drop spillways under submerged flow conditions.

Test Results: Outlet Tests

The test program for the study of outlets for box inlet drop spillways may be conveniently divided into three parts: the initial tests, the definition tests, and the check tests. The initial tests were exploratory in nature—that is, a number of different forms of the outlet were devised and tested to determine the important features of the outlet. The general form of the outlet evolved from these exploratory tests. The definition tests were made to define the design rules, to evaluate the design equations, and to determine the ranges of their application. The check tests covered the anticipated range of each of the variables and served to verify the design rules. In the following pages, each element entering into the design will be discussed in a manner that will permit the reader to verify, independently, the adequacy of the design data.

Since the form of the outlet is determined largely by the manner in which the flow leaves the box inlet, it is pertinent to describe the outflow briefly. The water passing over the sides of the box inlet springs clear of the sidewalls and creates a space between and under the nappes and the sidewalls. These spaces are filled with water having a helical motion about a horizontal axis. At the exit of the box inlet, the helices from the opposite sides of the spillway enter the outlet along the sidewalls and create a considerable disturbance and uneven distribution of flow across the outlet. It is this poor velocity distribution and attempts to improve it that cause the major problems in the development of the outlet.

Critical Depth

In order to determine the proportions of the outlet it is necessary to determine the critical depth at two points in the outlet—in the straight section (L_S in Fig. 2) and at the exit.

The equation for the critical depth in the straight section of the outlet d_c is

$$d_c = \sqrt[3]{\frac{(Q/W)^2}{g}} \tag{7}$$

where Q is the discharge, W is the width of the straight section, and g is the acceleration due to gravity.

At the end of the stilling basin the equation becomes

$$d_{ce} = \sqrt[3]{\frac{(Q/W_e)^2}{g}} \tag{8}$$

9. Loc. cit. Note 7.

where d_{ce} is the critical depth and W_e is the width of the stilling basin exit.

Straight Section

A straight section is used between the box inlet and the stilling basin to assist in breaking up the helical rollers described earlier, to improve the flow distribution, to make better use of the available tailwater, and to improve the scour pattern. The necessity for the straight section is shown in Fig. 17. In Fig. 17(a) the outlet sidewall has a flare of 1 in 3 for its entire length. The roller clings to the sidewall and at the stilling basin exit the high velocity is at the sidewall. This causes the high velocities to be along the sides of the downstream channel and results in scour of the banks and scour of the bed along the sides of the channel. In Fig. 17(b) the outlet sidewall first flares 1 in 1 in an attempt to give the roller a chance to spread out, then is made parallel to the outlet centerline. Although the rollers fall to the floor of the outlet and spread out, the transverse component of the velocity creates an impact wave against the sidewalls and high velocities along the walls. The uneven velocity distribution at the end of the outlet gives rise to eddies in the downstream channel and results in very poor scour patterns. In both of these models various combinations of baffles, angular sills, cross sills, longitudinal sills, and end sills were tried in an effort to obtain a satisfactory flow pattern, but no combination was successful.

After running tests with several types of sidewall, it was found that if a straight section (one having parallel sidewalls) equal to the box inlet in width were used between the box inlet and the outlet proper, the roller was broken up, the flow distribution was improved, better use was made of the tailwater, and the resulting scour pattern was improved. Fig. 17(c) shows the flow conditions where this straight section is used.

The data obtained from the tests made to determine the length of the straight section are plotted in Fig. 18 using as coordinates $(L_S/d_c) - 1$ and B/W. The selection of the coordinates was by trial and error. The curve drawn through the plotted data has the equation

$$L_S = d_c \left(\frac{C \cdot 2}{B/W} + 1 \right) \tag{9}$$

The points are scattered in Fig. 18 because of the manner in which the data were obtained. The rate of flow which gave good flow distribution over the end sill was determined only by visual observation. Therefore, for the same length of straight section, it is possible that two or more flows could be equally acceptable. Check tests on this portion of the outlet and tests on the other parts show that ordinarily Eq. 9 will give a straight section that is too short for practical use. When this occurs, the straight section may be lengthened to suit the site with assurance that it will function properly.

It will be noticed that B/W appears in the denominator of the equation. As B W approaches zero, the minimum length of the straight section therefore becomes infinite. This seems unreasonable. Eq. 9 is valid and should be used only for values of $B/W \geq 0.25$—the minimum covered by the tests. It is not intended that the outlet described here be used for straight overfalls such as would be the case if $B/W = 0$.
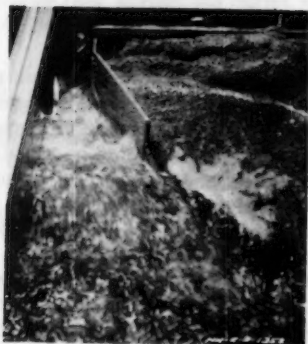
Stilling Basin Section

The stilling basin section of the outlet is used to remove destructive energy from the flow and to discharge water into the downstream channel in a manner
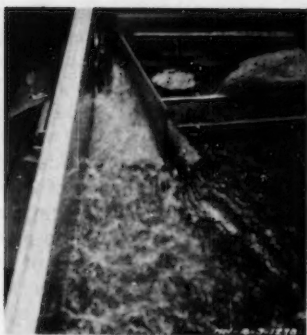
(a) Sidewall Flare is 1 in 3.
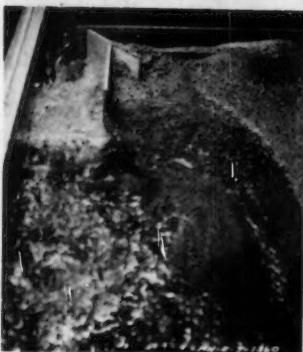
(b) Sidewall Flare is First 1 in 1
Followed by Parallel Sidewalls.

(c) Straight Section Followed by
Sidewall Flare of 1 in 2.

Fig. 17.--Effect of Various Sidewall Forms.

that will not damage the bed, the banks, or the structure itself. There are a number of elements that comprise the stilling basin, and the tests made on each of these elements will be discussed.
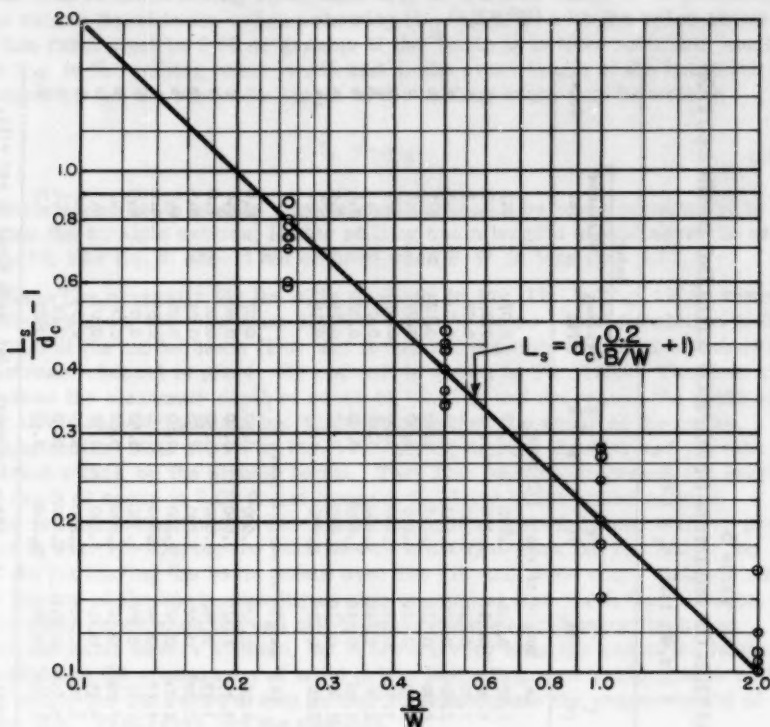

Fig. 18

Tests showed that the sidewalls either could be parallel extensions of the straight section sidewalls or could flare as much as 1 transverse in 1 longitudinal. If the sidewall flare is greater than 1 in 2, the flow does not spread out rapidly enough to follow the sidewalls, the main stream will be concentrated at the center of the stilling basin, and whirls will develop between the stream and the walls. The choice between the limits 1 in ∞ (no flare) and 1 in 2 depends on site conditions; these broad limits thus permit the adaptation of the outlet to almost any field situation.

Length.—Tests were run to determine the minimum length of the stilling basin for box inlets having shape ratios B/W of 2.0, 1.5, 1.0, and 0.5; a depth ratio W/D of 1; the previously determined straight section length; a tailwater depth of $1.6d_{ce}$; end and longitudinal sills W/8 high; and wingwalls set at a 45^0 angle and cut on a 45^0 top slope.

Observation showed that, for the short box inlets, the jet shoots out at a high level and takes a relatively greater distance to level out than for the longer boxes, and that the basin length must be proportionately greater for the

Table 5

TEST RESULTS FOR DETERMINATION OF MINIMUM LENGTH OF STILLING BASIN SECTION

$W = 0.667$ ft., $d_2 = 1.60d_0$

Run No.	Q c.f.s.	$\frac{B}{W}$	$\frac{D}{W}$	L ft.	L_s ft.	L_B ft.	$\frac{L_B}{W} \times \frac{B}{W}$	Scour Maximum[1] ft.	Scour Distance[2] ft.	Notes
(a) Length of run = 1/2 hour										
163	0.700	1.00	1.00	2.00	0.410	1.160	0.58	0.07	0.7	b
164	0.700	1.00	1.00	2.00	0.410	1.000	0.50	0.07	0.7	b
165	0.700	1.00	1.00	2.00	0.410	0.667	0.34	0.07	0.7	a
166	0.700	1.00	1.00	2.00	0.410	0.583	0.29	0.07	0.5	a
182	0.700	1.00	1.00	2.00	0.410	1.160	0.58	0.12	0.7	b
183	1.130	2.00	1.00	3.33	0.410	1.160	0.70	0.07	0.6	b
184	1.130	2.00	1.00	3.33	0.410	1.000	0.60	0.07	0.7	b
185	0.824	1.50	1.00	2.66	0.410	1.000	0.56	0.05	0.5	b
186	0.700	1.00	1.00	2.00	0.410	1.000	0.50	0.02	0.4	b
187	0.700	1.00	1.00	2.00	0.410	0.830	0.42	0.15	0.6	a
188	0.824	1.50	1.00	2.66	0.410	0.830	0.47	0.15	0.7	a
(b) Length of run = 4 hours										
358	0.530	1.00	0.50	2.00	0.324	1.000	0.50	0.07	0.8	b
359	0.810	2.00	0.50	3.33	1.330	0.830	0.50	0.06	0.6	b
360	0.800	2.00	1.00	3.33	0.590	0.830	0.50	0.07	1.0	b
361	0.305	1.00	0.25	2.00	0.224	1.000	0.50	0.03	0.5	b
363	0.530	1.00	0.50	2.00	0.324	1.200	0.60	0.08	0.7	b
365	0.810	2.00	0.50	3.33	0.396	0.830	0.50	0.05	0.6	b
369	0.345	0.50	0.25	1.33	0.288	1.330	0.50	0.03	0.5	b
371	0.305	1.00	0.25	2.00	0.224	1.200	0.60	0.06	0.7	b
373	0.328	2.00	0.25	3.33	0.218	1.200	0.72	0.03	0.5	b
374	0.400	1.00	0.25	2.00	0.268	1.200	0.60	0.05	0.2	b
375	0.105	2.00	0.25	3.33	0.247	0.830	0.50	0.02	0.1	b
386	0.750	1.50	1.00	2.66	0.390	0.880	0.55	0.07	0.7	b

Notes: 1. Below floor of stilling basin.

2. From end of stilling basin.

a. Basin too short. Jet lands close to end sill.

b. Basin length satisfactory.

same discharge. Where the box inlet is long, water shoots out from the bottom of the box and levels out in a relatively short distance, thereby requiring less basin length.

The data obtained during these tests may be found in Table 5. A comparison of the values listed in the column showing $(L_B/L)(B/W)$ with the notes shows that this ratio must be 0.50 or greater if the basin is to have sufficient length. Here L_B is the stilling basin length and L the crest length of the box inlet. The equation for the minimum length of the stilling basin may be written

$$L_B = \frac{L}{2B/W} \tag{10}$$

Greater stilling basin lengths may be used but it will be more economical to lengthen the straight section; lesser stilling basin lengths should never be used.

Eq. 10, like Eq. 9, should not be used when B/W is less than 0.25.

Sills.—The necessity for the sills is shown in Fig. 19. In Fig. 19(a), where no sills are used, the maximum depth of scour is below -0.20 ft relative to the elevation of the model basin floor and it was not possible to hold the bank of the downstream channel in place. An end sill is shown in Fig. 19(b). This end sill decreases the maximum depth of scour to -0.12 ft and decreases the depth of scour at the end of the basin but does not decrease the scour of the banks. The longitudinal sills shown in Fig. 19(c) straighten out the flow and prevent the direct attack on the stream banks. They also serve to decrease the maximum depth of scour to 0.08 ft and improve the form of the scour pattern.

The results of the tests to determine the best height of the end sill are presented in Fig. 20. During the tests it was noted that when the end sill is too high, the jet leaving the basin jumps over the sill and lands some distance out from the end of the basin, causing severe erosion at that particular location. On the other hand, when the end sill is too low the water leaving the basin causes the same severe erosion, but it occurs very near the end of the basin. This explains the appearance of solid points indicating poor performance both above and below the curve drawn in Fig. 20 to designate the proper height of the end sill. This curve has the equation

$$f = d_2/6 \tag{11}$$

where f is the height of the end sill and d_2 is the tailwater depth over the basin floor. The determination of the required tailwater depth is given in a later section of this paper.

Although several different heights of longitudinal sills were tested, it was found that the height which appeared to be most satisfactory was equal to that used for the end sill.

The longitudinal sills may be omitted if the stilling basin sidewalls are parallel extensions of the straight section sidewalls. They should be used whereever the stilling basin sidewalls flare. The longitudinal sills start at the exit of the box inlet and extend to the end sill. Tests showed that only a single pair of sills need be used if W_e is less than 2.5W. Their distance either side of the outlet centerline should be between W/6 and W/4. Where W_e is greater than 2.5W an additional pair of sills is required, and they should be located midway between the center pair of sills and the sidewalls at the stilling basin exit.

(a) No Sills.
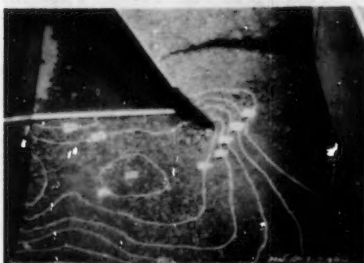
(b) End Sill Only.
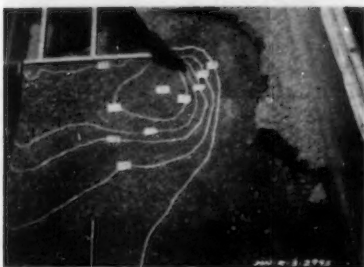
(c) End and Longitudinal Sills.

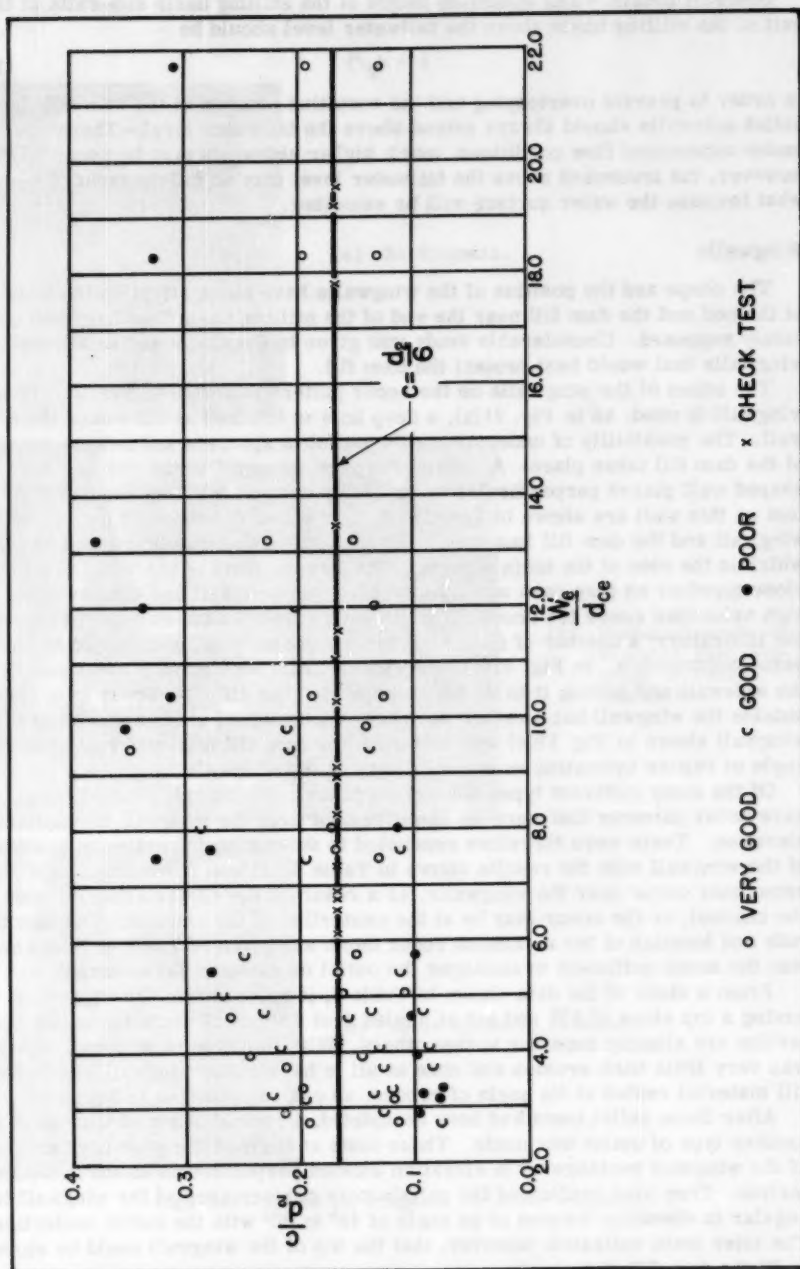Fig. 19.--Effect of Sills on Scour Pattern.
Contours are at 0.05-ft Intervals.

Fig. 20

Sidewall Height.—The minimum height of the stilling basin sidewalls at the exit of the stilling basin above the tailwater level should be

$$t = d_2/3 \tag{12}$$

In order to prevent overtopping and the resulting erosion of the dam fill, the outlet sidewalls should always extend above the tailwater level. Therefore, under submerged flow conditions, much higher sidewalls may be required; however, the freeboard above the tailwater level may be safely reduced some-what because the water surface will be smoother.

Wingwalls

The shape and the position of the wingwalls have more effect on the scour of the bed and the dam fill near the end of the stilling basin than has been com-monly supposed. Considerable study was given to the shape and location of wingwalls that would best protect the dam fill.

The effect of the wingwalls on the scour pattern is shown in Fig. 21. If no wingwall is used, as in Fig. 21(a), a deep hole is scoured at the end of the side-wall. The possibility of undermining the outlet is apparent and severe erosion of the dam fill takes place. A common type of wingwall is the rectangular shaped wall placed perpendicular to the outlet centerline. The results of the test on this wall are shown in Fig. 21(b). The scour is severe at the end of the wingwall and the dam fill has been badly eroded. The scour is caused by a whirl on the side of the main stream. The stream lines of the whirl are forced close together as they pass around the end of the wingwall and the resulting high velocities cause the scour. This is not an isolated case observed only in the laboratory; a number of field structures have been badly damaged by the same phenomenon. In Fig. 21(c), the wingwall has been formed by extending the sidewall and cutting it to fit the slope of the dam fill. No scour took place outside the wingwall but a rather deep hole was scoured at its end. When the wingwall shown in Fig. 19(c) was installed, the dam fill material rested on its angle of repose indicating no scour in back of the wingwall.

Of the many different types and arrangements of wingwall studied, none gave scour patterns that were an improvement over the wingwall triangular in elevation. Tests were therefore conducted to determine the optimum position of the wingwall with the results shown in Table 6. It was noted that slight scour may occur near the wingwalls, as a result of the eddies along the side of the channel, or the scour may be at the centerline of the channel. The magni-tude and location of the maximum scour depth are given in Table 6. In no case was the scour sufficient to endanger the outlet or cause undue concern.

From a study of the data shown in Table 6, it appears that the wingwalls having a top slope of 45° and set at angles θ of 45° and 60° with the outlet cen-terline are slightly superior to the others. With this type of wingwall, there was very little bank erosion and none at all in back of the wingwall where the fill material rested at its angle of repose, as can be observed in Fig. 19(c).

After these outlet tests had been completed, a special study of wingwalls for another type of outlet was made. These tests confirmed the poor performance of the wingwall rectangular in elevation located perpendicular to the outlet cen-terline. They also confirmed the satisfactory performance of the wingwall tri-angular in elevation located at an angle of 45° to 60° with the outlet centerline. The later tests indicated, however, that the top of the wingwall could be sloped to fit the dam fill if desired.

(a) No Wingwall.
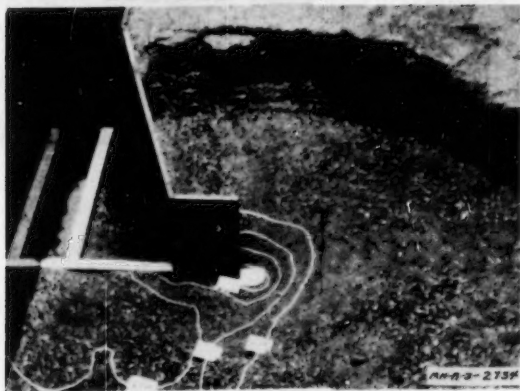
(b) Rectangular-shaped
     Wingwall Perpendi-
     cular to Outlet
     Centerline.
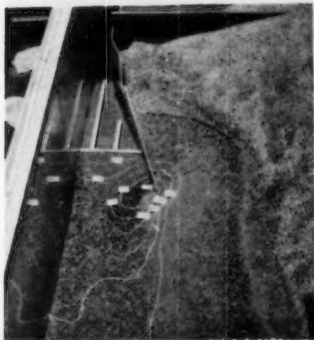
(c) Basin Sidewall Extended
     and Cut to Fit Fill Slope.

Fig. 21.--Effect of Wingwall on Scour Pattern.

Table 6
TESTS TO DETERMINE WINGWALL POSITION AND TOP SLOPE

$W = 0.667$ ft., $D = 0.667$ ft., $d_2 = 1.60 d_{ce}$, length of run = 4 hours.

Run No.	Q c.f.s.	B ft.	L_s ft.	L_B ft.	W_e ft.	Wingwall Position[1] degrees	Top Slope[2] degrees	Maximum Scour[3] Near Wingwall ft.	Near Centerline ft.
240	1.28	1.000	0.550	1.2	1.86	60	30	0.09	
241						45	30	0.13	
242						30	30	0.10	
243						60	37.5	0.06	
244						45	37.5	0.06	
245						30	37.5		0.03
246						30	37.5		0.07
247						60	45	0.03	
248						45	45		0.05
249						30	45	0.05	
250						45	33.5	0.10	
251						60	33.5	0.04	
252	1.28	1.000	0.550	1.2	1.06	30	30	0.07	
253						45	30	0.05	
254						60	30	0.02	
255						30	37.5	0.07	
256						45	37.5	0.03	
257						60	37.5	0.00	
258						30	45	0.02	
259						45	45	+0.01	
260						60	45	+0.02	
261	1.04	0.667	0.508	1.2	1.16	60	45		0.03
262						45	45		0.12
263						30	45		0.07
264						60	37.5		0.05
265						45	37.5		0.07
266						30	37.5		0.12
267						45	0*		0.13
268						45	30		0.07

Row						Angle from centerline	Angle from horizontal		Below floor of stilling basin
269	1.13	1.333	0.93	1.2	1.16	15	45	0.12	0.07
270						45	37.5	0.07	0.08
271						30	37.5		
272						30	37.5		
273						60	37.5	0.04	0.05
274						60	30	0.03	0.05
275						60	45	+0.02	0.07
276						15	45	0.02	0.07
277	0.80	1.333	0.93	1.1	1.03	60	37.5	0.05	0.07
278						45	37.5		0.07
279						30	37.5		0.04
280						60	45		0.03
281						45	45	0.07	0.02
282						30	30		0.02
283						15	30		0.02
284						15		0.07	0.02
285	0.69	1.000	0.360	1.1	1.03	60	37.5	0.05	0.02
286						45	37.5		0.02
287						30	37.5		
288						60	45		0.02
289						15	45		0.02
290						30	45		
291						45	30		
292						30	30	0.07	0.07
293						15	30	0.07	0.04
294	0.56	0.667	0.336	1.1	1.03	30	30		0.02
295						45	30		0.04
296						60	45	0.04	
297						15	45		0.02
298						30	37.5		0.04
299						30	37.5		0.03
300						45	37.5		0.03
301						15	37.5		0.03
302						30	37.5	0.03	0.03

Notes: 1. Angle from centerline. 2. Angle from horizontal. 3. Below floor of stilling basin.
*Rectangular wingwall; top horizontal.

Tailwater Depth

The tests to define the required tailwater depth were conducted before the sill heights had been determined, and the height of the longitudinal sills was taken as $W/8$ for this group of tests. The box inlets had relative lengths B/W of 0.5, 1.0, 1.5, and 2.0 and a relative depth D/W of 1. The length of the straight section was based on Eq. 9, and the wingwalls were set at an angle of 45° from the outlet centerline and cut on a 45° top slope.

The minimum depth of tailwater that would keep the hydraulic jump in the outlet was determined for each test. These minimum relative depths measured above the basin floor d_2/d_{ce} have been plotted in Fig. 22 as open circles against the relative widths of the exit of the stilling basin W_e/d_{ce}. Curves were drawn through these data and used for the subsequent tests. Up to the point where W_e/d_{ce} is equal to 11.5, the equation of the curve takes the form

$$d_2 = 1.6 d_{ce} \tag{13a}$$

While for values of W_e/d_{ce} in excess of 11.5, the equation of the curve is

$$d_2 = d_{ce} + 0.052 W_e \tag{13b}$$

Eq. 13(b) is used at the higher ratios of W_e/d_{ce} because the tests show that dead or nearly dead water exists along the wingwalls near the end of the basin when this ratio is greater than 11.5. That portion of the outlet occupied by dead water is obviously not being used to dissipate energy, and the outlet would operate just as well if it were eliminated. Satisfactory results can be obtained with outlets wider than $11.5 d_{ce}$ if the tailwater depth is computed from Eq. 13(b), but the wider basins result in inefficient use of the outlet and will likely be more expensive than a basin with a narrower outlet width.

The check tests, which were conducted using the recommended sill heights and tailwater depths computed from Eqs. 13(a) and 13(b), showed that these equations give satisfactory tailwater depths. The check tests are plotted in Fig. 22 as solid circles. Another group of tests conducted with tailwater depths greater than those given in Eq. 13 produced scour patterns as good as or better than those produced when the design tailwater depth was used.

Depth of Box Inlet

The depth of the box inlet was not ignored; it was considered in each step of the test program. However, it will be noted that the box inlet depth does not appear in any of the design equations. It is believed that this is due to the manner in which the water flows through the box inlet. The flow in the box is very turbulent and much of the energy at the drop is dissipated so that it is the depth of flow in the box inlet, which is related to the critical depth used in the outlet equations, rather than the box inlet depth itself that determines the proportions of the outlet.

Check Tests

The various elements comprising an outlet each have their individual effect on the performance of the structure. These effects are, of course, interrelated so that a variation in one element can possibly cause a change in the performance of some other element; yet, the only logical way to conduct the experiments was to vary only one element at a time and disregard, temporarily, its effect on the other elements. Therefore, in order to make sure that all interrelated elements were working together to insure the desired final result, a
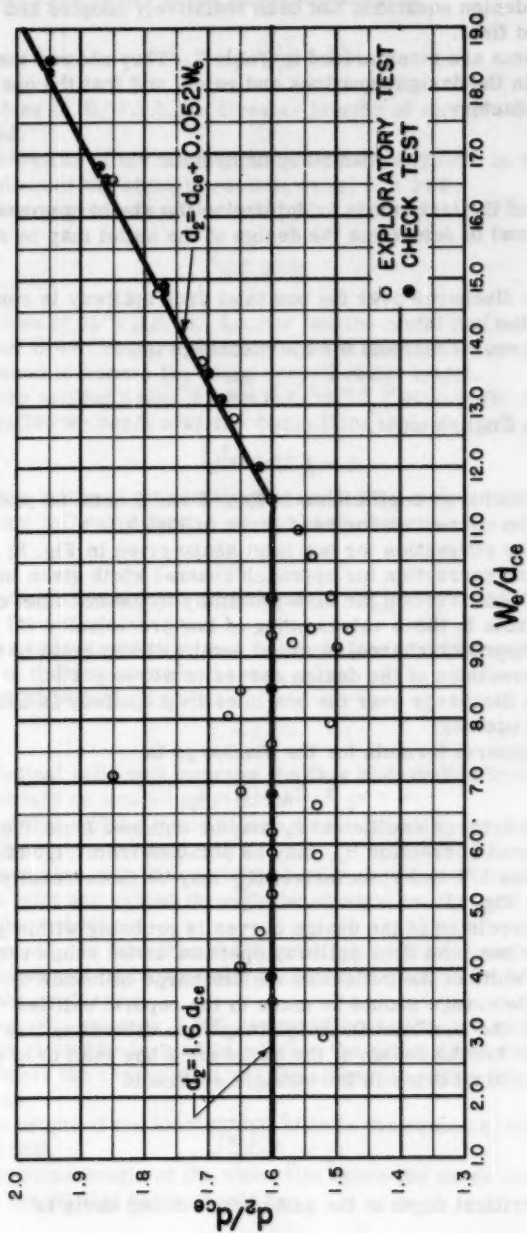
Fig. 22

comprehensive series of check tests was required. These check tests were made after the design equations had been tentatively adopted and before they were considered final.

The check tests are summarized in Table 7. They showed that no changes were required in the design equations and rules, and that the operation of the outlet was satisfactory.

Summary of Results

The results of the tests made to determine the discharge over box inlet drop spillways and to determine the design of the outlet may be summarized as follows.

A. When the discharge over the box inlet drop spillway is controlled by the crest of the box inlet:
1) The general formula for the discharge is

$$Q = 0.4275 \ L \sqrt{2g} \ H^{3/2} \tag{5}$$

or, in English units,

$$Q = 3.43 \ L \ H^{3/2} \tag{6}$$

2) The discharge coefficients in Eqs. 5 and 6 must be multiplied by:
   a) The correction for head given in Fig. 9;
   b) The correction for box inlet shape given in Fig. 8;
   c) The correction for approach channel width given in Fig. 7; and
   d) The correction for dike proximity to the box inlet crest given in Table 5, these values being of low precision.
3) The approach channel is silted level with the crest of the box inlet.
4) The precision of the design curves is within $\pm 7\%$.

B. When the discharge over the box inlet drop spillway is controlled by the headwall opening:
1) The general formula for the discharge is

$$Q = c_2 \ W \sqrt{2g} \ (H - H_{02})^{3/2} \tag{3}$$

2) The discharge coefficient c_2 may be obtained from Fig. 10.
3) The head correction H_{02} may be obtained from Fig. 12. If D/W is between $1/4$ and 1, inclusive, H_{02} may be more readily determined from Fig. 11.
4) The precision of the design curves is probably within $\pm 10\%$.

C. When the box inlet drop spillway operates under submerged conditions, both the width of the outlet and the discharge influence the submergence effect. Reference should be made to the reports entitled "Hydraulic Design of the Box Inlet Drop Spillway"[10] to determine this effect.

D. The rules for the design of the outlet for a box inlet drop spillway are:
1) The critical depth in the straight section is

$$d_c = \sqrt[3]{\frac{(Q/W)^2}{g}} \tag{7}$$

2) The critical depth at the exit of the stilling basin is

$$d_{ce} = \sqrt[3]{\frac{(Q/W_e)^2}{g}} \tag{8}$$

10. Loc. cit. Note 7.

534-36

3) The minimum length of the straight section is

$$L_S = d_c \left(\frac{0.2}{B/W} + 1\right) \tag{9}$$

for values of $B/W \geq 0.25$. Greater lengths of straight section may be used.

4) The sidewalls of the stilling basin may flare from 1 in ∞ (parallel extensions of the straight section walls) to 1 in 2.

5) The minimum length of the stilling basin is

$$L_B = \frac{L}{2B/W} \tag{10}$$

for values of $B/W \geq 0.25$. Longer lengths of stilling basin may be used but it will require less material if the straight section is lengthened to secure the same overall outlet length.

6a) When the stilling basin is less than $11.5d_{ce}$ wide at its exit, the minimum tailwater depth over the basin floor is

$$d_2 = 1.6d_{ce} \tag{13a}$$

6b) When the stilling basin is more than $11.5d_{ce}$ wide at its exit, the minimum tailwater depth over the basin floor is

$$d_2 = d_{ce} + 0.052W_e \tag{13b}$$

However, stilling basins as wide as $11.5d_{ce}$ may make inefficient use of the outlet.

6c) Greater tailwater depths may be used; lesser depths will cause more scour in the downstream channel.

7) The height of the end sill is

$$f = d_2/6 \tag{11}$$

8) Longitudinal sills will improve the flow distribution in the outlet. They should be located as follows:

a) When the stilling basin sidewalls are parallel, the longitudinal sills may be omitted.

b) The center pair of longitudinal sills should start at the exit of the box inlet and extend through the straight section and stilling basin to the end sill.

c) When W_e is less than $2.5W$, only two sills are needed. These sills should be located at a distance p of $W/6$ to $W/4$ each side of the centerline.

d) When W_e exceeds $2.5W$, two additional sills are required. These sills should be located parallel to the outlet centerline and midway between the center sills and the sidewalls at the exit of the stilling basin.

e) The height of the longitudinal sills is the same as the height of the end sill.

9) The minimum height of the sidewalls above the water surface at the exit of the stilling basin should be

$$t = d_2/3 \tag{12}$$

or greater. The sidewalls should extend above the tailwater surface under all conditions.

Table 7
RESULTS OF CHECK TESTS

W = 0.667 ft., wingwall position = 60° from centerline, wingwall

Run No.	Q o.f.s.	B ft.	D ft.	d_c ft.	L_s ft.	L_B ft.	Sidewall Flare	W_e ft.
358	0.530	0.667	0.333	0.270	0.324	1.00	4:1	1.16
359	0.810	1.333	0.333	0.358	1.330	0.83	3:1	1.20
360	0.800	1.333	0.667	0.355	0.390	0.83	4:1	1.08
361	0.305	0.667	0.166	0.186	0.224	1.00	4:1	1.16
362	0.395	0.333	0.333	0.221	0.311	1.60	4:1	1.46
363	0.530	0.667	0.333	0.270	0.324	1.20	3:1	1.46
364	0.960	1.333	0.667	0.401	0.600	1.87	4:1	1.62
365	0.810	1.333	0.333	0.358	0.396	0.83	3:1	1.20
366	0.240	0.333	0.166	0.159	0.224	1.60	2:1	2.26
367	0.345	0.333	0.166	0.202	0.288	1.50	6:1	1.16
368	0.240	0.333	0.166	0.159	0.224	1.50	3:1	1.66
369	0.345	0.333	0.166	0.202	0.288	1.33	4:1	1.32
370	0.405	1.333	0.166	0.225	0.247	1.50	3:1	1.66
371	0.305	0.667	0.166	0.186	0.224	1.20	6:1	1.06
372	0.400	0.667	0.166	0.223	0.268	1.40	2:1	2.06
373	0.328	1.333	0.166	0.196	0.218	1.20	6:1	1.06
374	0.400	0.667	0.166	0.223	0.268	1.20	3:1	1.46
375	0.405	1.333	0.166	0.225	0.247	0.83	4:1	1.08
376	0.810	1.333	0.333	0.358	0.396	1.60	4:1	1.46
377	0.690	0.667	0.333	0.321	0.387	1.60	6:1	1.13
378	0.675	1.333	0.333	0.317	0.348	1.60	6:1	1.13
379	0.690	0.667	0.333	0.321	0.387	1.40	4:1	1.36
380	0.675	1.333	0.333	0.317	0.348	1.20	2:1	1.86
381	0.395	0.333	0.333	0.221	0.311	1.70	6:1	1.23
382	0.960	1.333	0.667	0.401	0.600	1.87	6:1	1.28
383	0.860	1.000	0.667	0.373	0.422	2.47	∞:1	0.67
384	0.556	0.333	0.667	0.279	0.390	1.60	4:1	1.46
385	0.800	1.333	0.667	0.355	0.390	1.60	4:1	1.46
386	0.750	1.000	0.667	0.340	0.390	0.88	4:1	1.10

Notes: 1. Below floor of stilling basin.   2. From end of stilling

top slope = 45° from horizontal, length of run = 4 hours.

d_{oe} ft.	d_2 ft.	c ft.	Sidewall Height ft.	Scour Maximum[1] ft.	Distance[2] ft.	Location[3] ft.
0.187	0.299	0.050	0.400	0.07	0.8	a
0.242	0.387	0.065	0.516	0.06	0.6	b
0.257	0.413	0.070	0.548	0.07	1.0	a
0.129	0.196	0.033	0.260	0.03	0.5	a
0.131	0.210	0.035	0.280	0.03	0.6	a
0.160	0.257	0.043	0.344	0.08	0.7	a
0.222	0.340	0.056	0.452	0.10	0.4	b
0.242	0.387	0.065	0.516	0.05	0.6	a
0.070	0.187	0.031	0.248	0.06	0.6	a
0.140	0.224	0.037	0.300	0.02	0.6	a
0.087	0.172	0.028	0.228	0.06	0.7	a
0.128	0.204	0.034	0.272	0.03	0.5	a
0.123	0.197	0.033	0.264	0.07	0.2	b
0.138	0.220	0.037	0.292	0.06	0.7	a
0.105	0.212	0.035	0.284	0.06	0.5	a
0.144	0.226	0.038	0.300	0.03	0.5	a
0.132	0.212	0.035	0.284	0.05	0.2	b
0.164	0.262	0.044	0.348	0.02	0.4	a
0.212	0.340	0.057	0.452	0.03	0.9	a
0.226	0.362	0.060	0.484	0.07	0.8	a
0.223	0.356	0.059	0.476	0.07	0.7	a
0.200	0.322	0.053	0.428	0.03	0.4	b
0.160	0.257	0.043	0.344	0.07	0.4	b
0.147	0.237	0.039	0.316	0.07	0.6	a
0.259	0.415	0.070	0.552	0.07	0.8	a
0.373	0.595	0.100	0.802	0.07	0.8	a
0.165	0.268	0.045	0.356	0.07	0.3	b
0.210	0.337	0.056	0.448	0.07	0.4	b
0.244	0.390	0.065	0.520	0.07	0.7	a

basin. 3. Location of maximum scour
    a. Near centerline
    b. Near wingwall

10a) The wingwalls should be triangular in elevation and have a top slope of 45° with the horizontal. Top slopes as flat as 30° are permissible.

10b) The wingwalls should flare in plan at an angle of 60° with the outlet centerline. Flare angles of 45° are permissible. Wingwalls parallel to the outlet centerline are not recommended.

ACKNOWLEDGMENTS

APPENDIX I.   NOTATION

The following letter symbols, adopted for use in this paper and for the guidance of discussers, conform essentially to the American Standard Letter Symbols for Hydraulics (ASA—Z10.2—1942), prepared by a Committee of the American Standards Association, with Society representation and approved by the Association in 1942. In addition, the symbols of linear concepts are defined by Fig. 2.

A cross-sectional area of approach channel

B length of box inlet

c with subscripts, coefficients of discharge

D depth of box inlet

d_2 height of tailwater above basin floor

d_c critical depth in straight section

d_{ce} critical depth at stilling basin exit

$\underline{F}$ Froude number

f height of end and longitudinal sills

g acceleration due to gravity

H specific head; depth of flow plus velocity head = $h + h_v$

H_0 apparent specific head at zero flow; zero-flow head correction

Subscript "1" refers to control at box inlet crest.

Subscript "2" refers to control at headwall opening.

H_t level of tailwater referred to crest of box inlet

$\triangle H$ increase over free flow head caused by high tailwater level

h piezometric head

h_v velocity head = $V^2/2g$

L length of box inlet crest = $2B + W$

L_S minimum length of straight section of outlet

L_B minimum length of stilling basin section of outlet

n exponent

p spacing of center pair of longitudinal sills either side of outlet centerline

Q discharge

r spacing of outer pair of longitudinal sills

t minimum height of sidewall at basin exit above tailwater elevation

V mean velocity = Q/A

W width of box inlet

W_c width of approach channel

W_e width of stilling basin exit

X distance from box inlet crest to toe of dike

θ angle wingwall makes with outlet centerline